End-of-life solar photovoltaic waste management: A comparison as per European Union and United States regulatory approaches

Preeti Nain, Annick Anctil
Department of Civil and Environmental Engineering, Michigan State University, East Lansing, Michigan, 48824, USA

Abstract

The increasing growth of solar photovoltaic (PV) deployment raises end-of-life management concerns. Previous studies have forecasted PV waste; however, the implications of the regulations were not assessed. The present study estimates the volume and composition of end-of-life solar PV waste for the European Union and the United States. The recycling potential of generated waste and the fate of materials in end-of-life PV waste as per the present regulations is also estimated. Further, the work analyses solar manufacturers contributing to the waste and provides recommendations for improving solar PV waste management. The analysis in the present study shows that 24.93 million tonnes and 36.23 million tonnes (metric ton) of PV waste with an economic value of 189 billion USD and 262 billion USD are expected to be generated between 2025 and 2050 in the US and European Union, respectively. This work also indicates that the US lacks federal PV waste-specific management regulations and has different requirements across the states. In contrast, European countries have adopted the Waste Electrical and Electronic Equipment Directive in their national legislations in addition to country-specific PV manufacturer compliance schemes. Due to the lack of regulations, 20 MT of PV waste is expected to be disposed of in landfills in the US. Chinese manufacturers like Tongwei, Aiko, and LONGi are leading manufacturers of PV shipments globally. They could play a significant role in PV recycling and management if they adopt take-back programs and invest in recycling, contributing to future end-of-life PV waste management. In light of these observations, a need for greater synchronization between federal and state-level end-of-life PV regulations, collaboration among recyclers and PV industry stakeholders, and continued research and knowledge sharing is recommended. Secondly, incorporating emerging contaminants in PV waste regulations and waste characterization methods is required for responsible recycling and safe management.

Keywords: Solar photovoltaic, Solar PV waste, End-of-life regulations, Emerging contaminants

1. Introduction

1.1 Solar PV installations

Solar photovoltaic (PV) has been one of the fastest-growing renewable energy technologies due to continuous decline in cost and increase in efficiency. PV installations are projected to supply 25% of the world's electricity demand by 2050 [1]. China (cumulative capacity, 414.5 GW), the European Union (209.3 GW), and the United States (141.6 GW) (Fig. 1) ranked as the top three with the highest PV installations in 2022 [2]. Energy and environmental benefits from PV technology have been widely studied, showing PV modules have lesser environmental impacts than other energy technologies [3]. As per IPCC, the CO_2 emissions per kWh of electricity generated for rooftop solar PVs is approximately 12 times less than natural gas and 20 times less than coal [4]. However, the increasing deployment triggers end-of-life (henceforth, EoL) management concerns.

On average, the service or technical life of a typical crystalline PV module is 25 years; nowadays, some advanced modules come with a warranty of 30 years. As per a PV manufacturer, a solar module reaches its EoL if the maximum power loss exceeds 20% of the rated capacity [5]. Most of the current PV waste stream mainly consists of defective modules produced during manufacturing, damaged modules due to transportation, and modules retired after a few years of operation [6]. For economic benefits, old PV modules with low power conversion efficiency are sometimes replaced with new modules with better efficiency. The exponential increase in PV installations will lead to massive EoL waste in the coming decade. Thus, understanding approaches, mechanisms, and regulations is needed to ensure the sustainable management of EoL solar PVs.

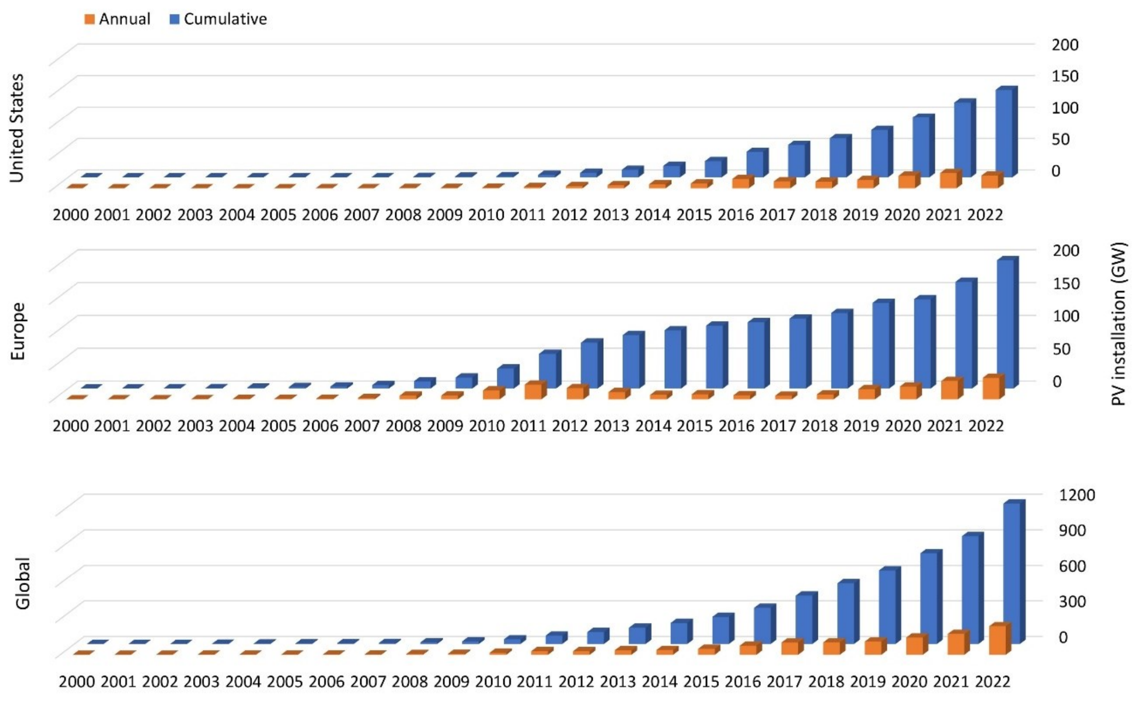

Fig. 1: Annual and Cumulative PV installations (data from SEIA [7], IEA [8], IRENA [9], and EPIA [10])

1.2 PV waste and material estimation needs for EoL management

PV modules vary by materials, size, weight, performance, and technology. The most installed technologies are crystalline silicon (c-Si) and thin-film (cadmium telluride), but c-Si PVs dominate the current installations. Policy support (auctions, feed-in tariffs, net metering), continued technology advancements and cost reductions are the principal drivers for the extensive deployment of silicon modules worldwide [8]. Thus, it is expected that c-Si PVs will have a significant share in the EoL PV waste stream in the coming decades, and a solution for managing it is a foremost requirement [11].

The typical structure of a c-Si module consists of a silicon layer coated with a metallization paste and embedded between two layers of Ethylene Vinyl Acetate (EVA). A top glass layer and PET- (Polyethylene Terephthalate) based back layer provide physical protection and complete the sandwich structure. This is finished with a junction box (mainly made of plastic) connecting solar modules to the inverter and, ultimately, the grid [12]. Although reduction and reuse are preferred in conventional waste management frameworks, recycling end-of-life material must be considered to minimize incineration and landfilling. On average, more than 80% of the module weight comprises glass and aluminum frames [13], and more than 95% of the total module mass is recoverable [14]. Still, metals like magnesium and nickel have a lower recovery rate, which is understandable, considering they represent less than 1% of the module weight [15]. Thus, understanding the volume and material content of the upcoming c-Si PV waste stream is crucial for suitable EoL management.

Various studies in the past forecasted PV waste streams and included material amount and composition [16-19]. The International Environmental Agency forecasted the cumulative PV waste volumes as 80 million tons by 2050 [9]. However, investigations on the fate of these materials concerning present regulations are lacking. Due to inconsistency in PV installations and failure data, different studies present different waste volumes. Thin-film modules like CdTe are collected and recycled [20] into new modules, so they shouldn't be of concern in future PV waste. Approximately 25,000 tons of spent CdTe modules are recycled worldwide annually with a recovery rate of over 90% [21]. Thus, a study investigating the fate of c-Si PV waste as per the regulations is required to better understand the current situation.

1.3 PV waste regulations status

Several countries are establishing policy measures and managerial initiatives to minimize EoL PV waste and avoid adverse environmental impacts of improper disposal [22]. Germany, Australia, Spain, Italy, Japan, and the United States have recently introduced various management options to tackle PV waste [9, 23]. The European Union has been a forerunner in regulating PV waste by passing waste electrical and electronic equipment (WEEE) directives and creating the PV Cycle organization. The WEEE directive encourages solar module recovery, reuse, and recycling by implementing Extended Producer Responsibility [24]. PV Cycle offers collective waste management and legal compliance services for handling solar and other electronic wastes worldwide [24, 25]. As the EoL PV waste increases, it is crucial to assess the present regulatory framework to understand the present management frameworks addressing various contaminants and suggest required future actions [19, 24, 25]. As per the author's knowledge, no study applied the current regulations to estimate PV waste to assess the disposal fate at end-of-life.

1.4 Objectives and Scope

The objectives of this study are to (1) estimate PV waste amount in the EU and the US and the material composition and recycling potential of PV waste; (2) provide a comprehensive overview of existing PV-waste-specific regulations and approaches adopted by the EU and the US, and the fate of PV waste as per the regulations; and (3) suggest prospective options for safely managing PV waste streams. To achieve these objectives, the study is structured according to Fig. 2. Overall, the findings from the objectives answer the question, "What amount of PV waste will be generated in the US and EU, and what will be the composition? What are the PV-waste specific regulations, and what will be the fate of PV waste as per these regulations?"

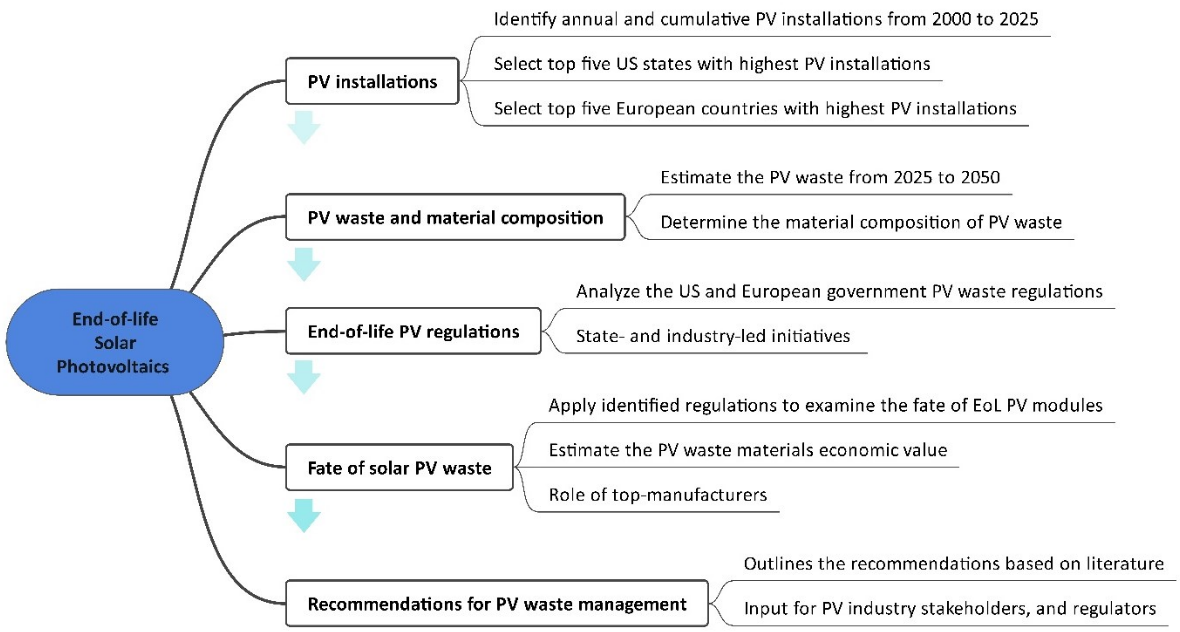

Fig. 2: Overview of the present study.

2. Methodology

The present study estimates the PV waste volumes by compiling data from the existing literature and assessing the disposal fate of PV waste as per the present applicable regulations. The five US states and five European countries with the highest cumulative PV installations are considered. The following approach estimates the material contained in PV installations, which will become PV waste, along with their fate, i.e., recycling or landfill, depending upon the regulation. A similar methodology is applied in the literature [26] and has been expanded to ten locations in the present study. This methodology is applied in the following steps:

2. 1 Estimate the PV waste volume and material content by 2050.

The first step to estimate PV waste is to identify annual and cumulative PV installations in the last two decades. Several sources report PV installations globally, but not all provide PV deployment data state- and manufacturer-wise. Data from NREL and SEIA is the primary input to compile installed PV capacity annually in the five US states (California, Texas, Florida, North Carolina, and Arizona). For European countries, EPIA, EurObserv'ER, and EU annual PV status reports are used to summarize PV installations. Germany, Italy, Spain, France, and the Netherlands are considered. The annual PV installations from 2000-2022 and projected installation in the next three years are compiled for selected US states and European countries. An average life of 25 years is considered for modules. The installation year makes it possible to estimate the PV module's disposal year.

This work focuses only on crystalline silicon modules since it represent 95% of installed modules globally [27]. The assumptions for the material composition of a silicon PV module are summarized in Table 1. As the modules have been installed in the last 20 years, module specifications like area, power, efficiency, and weight are considered from the Ecoinvent 3.3 database. The PET or plastic fraction of the back sheet and junction box/cables are represented cumulatively as “plastic” in estimated PV waste (as shown in Table 1). The number of modules is calculated by dividing the total installed PV capacity by the nominal module power. Once the module number is known, the total mass of PV waste is calculated by multiplying the module’s number by the module weight. The economic value of materials in PV waste is estimated by multiplying the amount by Bloomberg commodity price rates [31]. To estimate the material content in PV waste, waste composition shown in Table 1, and Equation 1 are used.

$$Material\ content\ (kg) = \frac{Installed\ capacity\ (W) \times Composition\ \left(\frac{kg}{m2}\right) \times Module\ market\ Share\ (\%)}{Module\ power\ (W/m2)} \qquad [1]$$

Table 1: Material composition of crystalline silicon photovoltaics and recycling yield

Panel component	Material	Material fraction, %	Material, kg/m^2	Recycling yield, %	Reference
Frame	Aluminium	14.70	2.32	100	Sah et al. (2022); Dominguez and Geyer, (2019); Duflo et al. (2018)
	Steel	8.65	1.36	100	
Junction box & cable	Copper	1.90	0.30	95	
	Plastic	2.85	0.45	95	
Encapsulant	EVA	4.52	0.71	75	
Backsheet	PET	1.91	0.30	75	
Front glass	Glass	59.51	9.37	98	
Solar cell layer	Silicon	1.00	0.16	95	Sah et al. (2022); Farrell et al. (2020); Dominguez and Geyer, (2019); Mahmoudi et al. (2019); Duflo et al. (2018); Corcelli et al. (2018); Dominguez and Geyer, (2017); Latunussa et al. (2016)
	Aluminium	2.00	0.32	100	
	Copper	2.00	0.32	95	
	Silver	0.12	0.02	95	
	Nickel	0.001	0.0002	41	
	Lead	0.01	0.002	98	
	Magnesium	0.50	0.08	33	
	Other metals	0.33	0.05		
Specifications	Area, m^2	1.46			Ecoinvent 3.3
	Power, Wp	224			
	Efficiency, %	15.3			
	Weight, kg	23			

2.2. End-of-life regulations and resulting PV waste fate

The second part of the study analyzed the literature for US and European government regulations, industry policies, and initiatives that address EoL PV waste management. Publicly available documents related to EoL PV waste management in the US and Europe from academic databases, government websites, and private organizations were collected. The resulting documents on keyword searches such as 'US or European EoL PV waste regulations or policies or initiatives' in Google Scholar and Google were reviewed and analyzed for summarizing EoL PV waste regulations. Along with federal regulations, state- and industry-led initiatives and policies were also summarised. The identified regulations are applied to examine the fate (landfill or recycling) of EoL PV modules. This analysis provides insights into the current regulations, practices, and management options. The data on the top ten solar PV manufacturers (by shipments, GW) from 2015-2022 were compiled from NREL solar industry update reports and analyzed for their role in EoL PV management [28].

At last, recommendations for PV waste management framework considering various factors like pollutants, regulations, PV waste volume, and handling options are provided. These can assist PV industry stakeholders, regulators, and waste managers.

3. Results and Discussion

3.1 PV waste estimation and Material composition

Future PV waste volumes are estimated for the US and Europe (Table 2) and, further, for the five US states and five European countries. The considered US states and EU countries represent approximately 45% and 75% of 2022 cumulative installed PV capacity, respectively. The PV capacity installed from 2000-2025 is considered to be decommissioned after 25 years of operational life. The results are presented in Figures 3 and 4. The expected number of waste PV modules between 2025-50 is 1.08 billion for the US and 1.57 billion for Europe. The mass of these waste PV modules is expected to be approximately 24.93 MT and 36.23 MT (MT: million metric ton), respectively, of which the major share is glass (14-19 MT) and aluminum (4-5 MT). With time, the advancement in materials and technologies will lower the total mass and modify the material's composition. The glass share might increase due to the increasing share of bi-facial modules in non-residential sectors [29].

Fig. 3 shows the mass fluxes of the PV waste stream for the US and Europe. This waste material doesn't include materials from mounting structures, inverters, or cables. Glass (US: 14, EU: 20 Million Tons), aluminum (US: 4, EU: 5.5 MT), steel (US: 2, EU: 2.8 MT), copper (US: 9.2, EU: 12.8 MT), and plastic (US: 1.1, EU: 1.6 MT) share most of the material mass of PV waste. Other metals like magnesium, lead, and nickel will represent smaller portions of EoL PV waste, yet with high economic value (5-7 MT for Ni and Pb and 392-544 MT for Mg), in the next 25 years. Thus, such a massive waste stream will result in a large EoL market for solar PV modules in the long term. Also, it is evident that c-Si PV waste will increase suddenly after 2040. Recycling these materials will provide substantial environmental and economic benefits. Monitoring temporal changes in modules' material intensity and regional deployment could help decide the recycling facilities' scale and location [30].

The recycling potential, shown in Fig. 3, for US and European PV waste, is presented based on the materials recycling yield (amount of material that can be recovered) given in Table 1. Assuming a 95% recycling yield, approximately 27,000 tons and 37,500 tons of silver can be recovered from PV modules installed between 2000 and 2025. Aluminum and steel have a 100% recycling yield, resulting in 3.9 Mt (US), 5.5 Mt (Europe), and 2 Mt (US), 2.8 Mt (Europe) of aluminum and steel recycling potential, respectively. Further, advancements in recycling technologies will increase recycling yields. Critical metals like nickel and silver may have higher recycling potential in the future. However, due to the longer operational lives of PV modules, the PV recycling facilities and infrastructure are not yet developed, and the recycling industry is still in the developmental stage.

With respect to economic value (USD), glass (US: 137B, Europe: 191B) and silver (US: 21B, Europe: 29B) are the top two materials based on the Bloomberg commodity price rates [31]. A previous article reported that materials recovered from EoL modules generated by 2050 in the US could be used to produce 2 billion new modules [32]. Technology advancement can affect the share of silver in future solar modules due to lower metallization paste usage. Silver is the main contributor to the PV recycling market revenue. The present analysis considered 20 g/m^2 of silver in c-Si modules, which is expected to decline by 70%

[32]. With time, the high reduction in silver content puts downward pressure on the recycling economics. Material substitutions from silver to copper or aluminum can lower the cost and change the overall economic value of materials in future EoL PV waste. The amount of silicon is further reduced in new modules with thinner wafers, thus reducing the recycling profitability. However, replacing lead-tin solder with lead-free solder or electrically conductive adhesives could reduce the lead handling cost during recycling [33].

As PV installations continue to increase, the demand for critical materials will also increase; thus, estimating materials in the end-of-life PV stream is essential to planning their recycling and recovery. Recovering critical materials from PV waste (i.e., urban mining) can provide economic benefits to plant owners, meet the demands for future PV installations, and pave the way to affordable clean energy. The IRENA report identifies minerals like nickel, copper, and magnesium as critical materials for clean technologies in the US and EU [34]. The findings from the present study estimate 118,419 tons and 164,460 tons of recoverable magnesium for the US and EU in the 2050 PV waste. Further, the PV waste has 237-329 tons of recoverable nickel with an economic value of 5-7 million USD. Loss of these materials can result in significant material and economic loss.

The US solar industry is a 50-state market historically dominated by states like California, Massachusetts, New Jersey, and New York. Presently, California is the leading state in US PV installations, followed by Texas, Florida, North Carolina, and Arizona. In 2022, 60% of US PV installations were in these states. Further, in the first quarter of 2023, the PV installations in California and Florida represented 35% of the US PV capacity [35]. Overall, the US PV installation has increased by 65% in the last decade [26]. Fig. 4 shows the estimated EoL PV modules between 2043 to 2048 along with their material composition. The quantity of materials in PV waste in 2048 is less compared to 2047 in the US because of 13% lower PV deployment in 2022 than in 2021 [7]. Further, the PV repowering or early replacement of lower-efficiency PV modules with more efficient ones [36], can change the findings in the present study which should be incorporated in future work. Ongoing research to identify second-life applications for these early retired PV systems can lower the increasing volumes of solar PV waste [37].

As seen in Fig. 5, the five US states considered in the present study represent roughly half of the US EoL PV waste stream. California and Texas are the top two US states responsible for 22.11% (3.16 MT) and 9.62% (1.38 MT) of the total US PV waste. Other US states represent 54.59% of the US PV waste going to be generated in 2044. The US PV deployment is expected to increase further from 153 GW in 2023 to 375 GW by the end of 2028 due to the tax incentives by the Inflation Reduction Act [38]. The rapid cost reduction of PV modules (more than 40% in the last decade) is expected to further increase nationwide solar system deployment. A recent study observed a notable decline in aluminum usage in the crystalline silicon modules produced from 2008 to 2021 [30]. The decrease is primarily due to thinner modules, simplified frame designs, and larger module sizes. However, concerning other materials like glass, the intensity has remained constant from 2008 to 2021, as the transition towards thinner glass appears to be progressing more slowly. The impact of these temporal variations in the material intensity on the PV waste estimations needs to be incorporated into future work.

Due to previous investments in PV, Germany has led the PV installations in the last decade. Laws mandating the purchase of renewable generated electricity, such as the Electricity Feed Law, 1990 and the Renewable Energy Law, 2000, played a significant role in PV deployments [39]. Germany forecasts an 80% share of renewable generated electricity by 2050 and benefits from PV systems about 56–75 billion € by 2030 [40]. As a result, the waste stream is expected to reach 2 MT with 1.1 billion modules in 2035. This waste stream primarily consists of crystalline silicon modules. The large volume of this stream requires cost-effective and higher recovery recycling processes.

Other countries in the European Union, such as Italy, Netherlands, Spain, and France, are among the top five countries in PV waste after Germany (Fig. 5). Italy has the second largest PV deployment capacity (22.1 GW), with a 14% share in 2020, which is expected to be doubled by 2030 [41]. The Netherlands is the third country in PV deployment capacity in the EU. The Netherlands solar power share in the country's electricity mix has increased from 1% in 2014 to 16% in 2022 because of value-added tax removal on residential solar PV systems and a decline in cost (around 70% in last ten years) of PV systems since 2014 [42]. As shown in Fig. 5, Italy and the Netherlands have approximately 13% and 10% share in EoL PV waste stream based on 2000-2022 installations. The installations from 2018 to 2022 have a significant share in going-to-be-generated PV waste (Fig. 3). Other countries like France and Spain that installed high PV capacity after 2017 will witness a considerable amount of EoL PV waste in 2032. France already has a recycling facility processing 4,000 tons of solar waste annually [39]. More academic research, timely capital allocation, and publicly available data on EoL PV modules could help plan for additional PV recycling facilities.

3.2 Leading PV manufacturers

In 2022, more than 95% of global PV installations are crystalline type. Compared to 2017, the installations from the top 10 global manufacturers grew from 46 GW to 200 GW in 2022 [43]. Some manufacturers ship more than 30 GW annually (Fig. 6). A number of new manufacturers like Aiko became one of the top 10 leading companies through the rapid growth of mono-Si modules in the last few years. Companies like LONGi, JA Solar, Canadian Solar, and Tongwei remained in the top ten manufacturers in the past few years [38], indicating most of the global PV waste stream with their modules.

Chinese PV manufacturers have generally been profitable since 2019 [35], due to increased PV demand and a drop in poly-silicon prices. In 2023, the module prices were recorded as the lowest ever at \$0.17/W because of competition among manufacturers and a decline in the value of the Dollar vs. Yuan. The solar industry update reports from the National Renewable Energy Laboratory (NREL) and corporate guidance from these manufacturers (Canadian Solar, First Solar, JA Solar, Jinko Solar, Longi, Risen, Trina, Tongwei) show that 2023 shipments will be 71% higher than 2022 [35]. Most of the world's top PV manufacturers in the last decade are from China, a few from Japan (Sharp Solar) and the US

(First Solar, Sunpower). A recent study has shown that Canadian Solar and Trina Solar might have strategies to reduce material use in module assembly and, thus, lower overall manufacturing costs [30]. Both manufacturers have shown notable variations in aluminum intensity, with an overall decrease from 2011 to 2021. This suggests the consideration of temporal variation in the density of various materials in future PV waste estimation studies.

In the US, 64% of PV installations in 2022 were utility-scale PV systems, highlighting the critical role of utility plant owners in PV waste management. Apart from the EoL of PV waste, the failure of solar components is a growing concern for US utility solar plants. A recent article reported that inverters fail halfway through a solar panel's operational lifetime [44]. This highlights the need to manufacture replacement components to harness the complete life of a module. In extreme natural events such as tornados or ice storms, existing modules and components are damaged, generating more PV waste. The question arises: who will take responsibility for the spent and replaced modules? Maybe the insurance companies could require leading manufacturers to pay compensation only if the replaced modules are refurbished and reused at other sites. Or the utility owners may ask PV manufacturers to repair or replace the failed components. This way, insurance companies and utility owners can push all the leading manufacturers to the EoL management. However, irrespective of forced responsibility and handling, leading manufacturers could support the PV recycling market by volunteering in recycling activities.

The present study did not consider the repowering aspect in PV waste estimation, and future studies are required to assess the repowering magnitude and fate of replaced modules. Volunteered manufacturers groups can create new platforms for reusing the replaced modules and explore recycling business models to increase PV circularity.

Table 2: Expected end-of-life PV modules for the US and Europe between 2025-2050.

Installation Year	United States				European Union				Disposal Year
	Annual capacity (GW)	Cumulative capacity (GW)	End-of-life PV modules (Million units)	Mass of EoL PV modules (Million tonnes)	Annual capacity (GW)	Cumulative capacity (GW)	End-of-life PV modules (Million units)	Mass of EoL PV modules (Million tonnes)	
2025*	40.0	242.8	178.6	4.1	55.0	337.2	245.5	5.6	2050
2024*	35.0	202.8	156.2	3.6	44.0	282.2	196.4	4.5	2049
2023*	28.5	167.8	127.2	2.9	42.8	238.2	191.1	4.4	2048
2022	20.2	139.3	90.2	2.1	32.82	195.4	146.5	3.4	2047
2021	24.0	119.1	107.1	2.5	28.0	162.7	125.0	2.9	2046
2020	19.8	95.1	88.4	2.0	19.6	136.1	87.5	2.1	2045
2019	13.2	75.3	58.9	1.3	15.63	130.7	69.8	1.6	2044
2018	10.5	62.1	46.9	1.1	7.50	115.1	33.4	0.8	2043
2017	11.0	51.6	49.1	1.2	5.56	106.6	24.8	0.6	2042
2016	14.7	40.6	65.6	1.5	6.26	101.1	27.9	0.6	2041
2015	7.5	25.9	33.4	0.8	7.80	95.84	34.8	0.8	2040
2014	6.3	18.4	28.1	0.7	6.95	88.64	31.1	0.7	2039
2013	4.7	12.1	20.9	0.5	10.97	81.49	48.9	1.2	2038
2012	3.4	7.4	15.2	0.3	17.16	70.04	76.6	1.8	2037
2011	1.9	4.0	8.5	0.2	22.41	52.88	100.0	2.3	2036
2010	0.8	2.1	3.6	0.08	13.62	30.47	60.8	1.4	2035
2009	0.38	1.3	1.7	0.04	5.83	16.85	26.1	0.6	2034
2008	0.29	0.92	1.3	0.03	5.71	11.02	25.5	0.6	2033
2007	0.16	0.63	0.7	0.01	2.03	5.31	9.1	0.2	2032
2006	0.11	0.47	0.5	0.01	0.99	3.28	4.4	0.1	2031
2005	0.08	0.36	0.4	0.008	0.98	2.29	4.4	0.1	2030
2004	0.06	0.28	0.3	0.006	0.71	1.30	3.2	0.07	2029
2003	0.04	0.22	0.2	0.004	0.20	0.59	0.9	0.02	2028
2002	0.02	0.18	0.09	0.002	0.13	0.39	0.6	0.02	2027
2001	0.02	0.16	0.09	0.002	0.13	0.26	0.6	0.02	2026
2000	0.14	0.14	0.6	0.014	0.06	0.13	0.2	0.06	2025
			1,083.9	**24.93**			**1,575.3**	**36.23**	

*: projected capacity; 1 Million units: 10^6 units; 1 Million tonnes: 10^9 Kg.

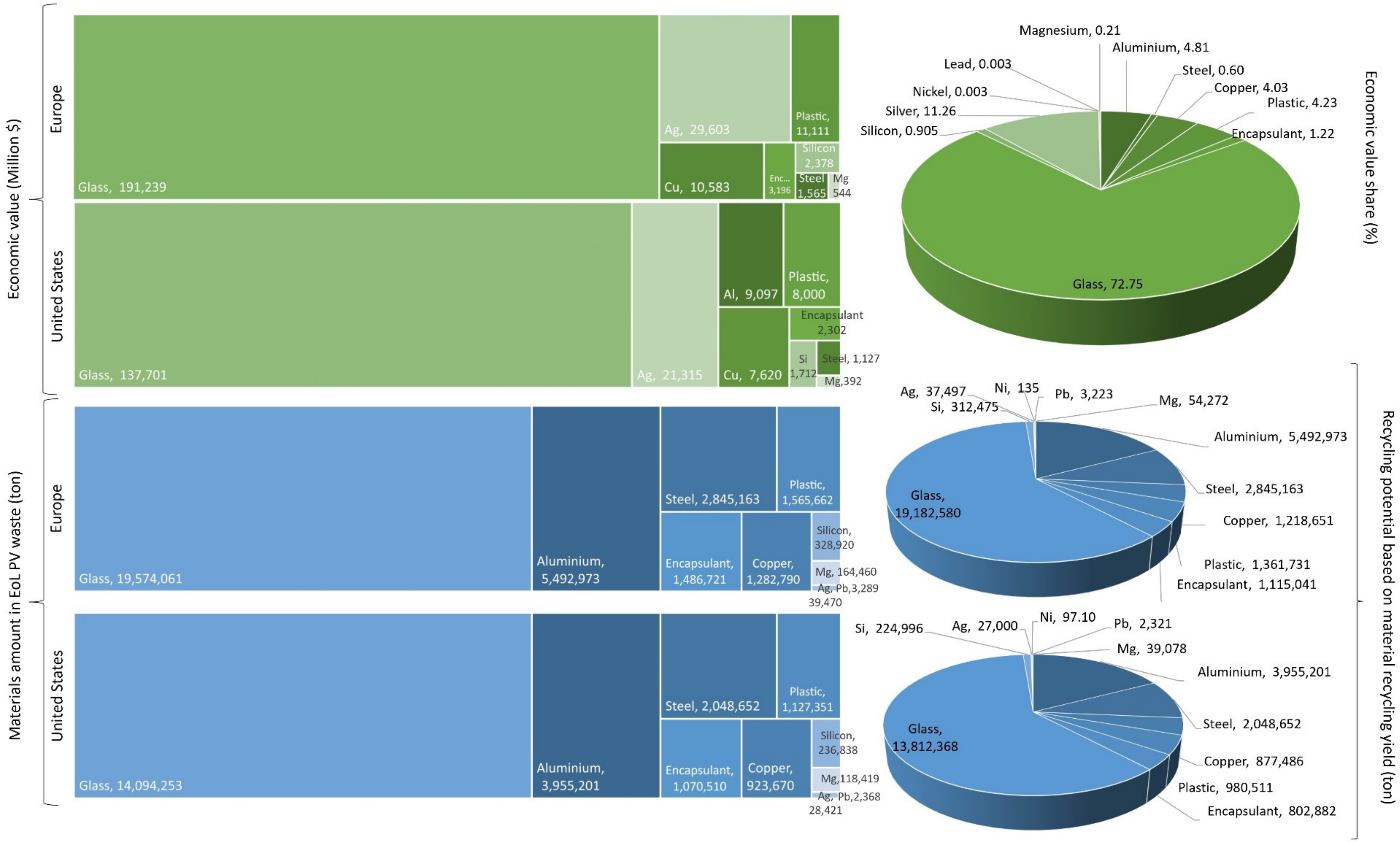

Fig. 3: Material's quantity, recycling potential, and economic value in end-of-life crystalline solar PV waste between 2025-2050 for the US and Europe.

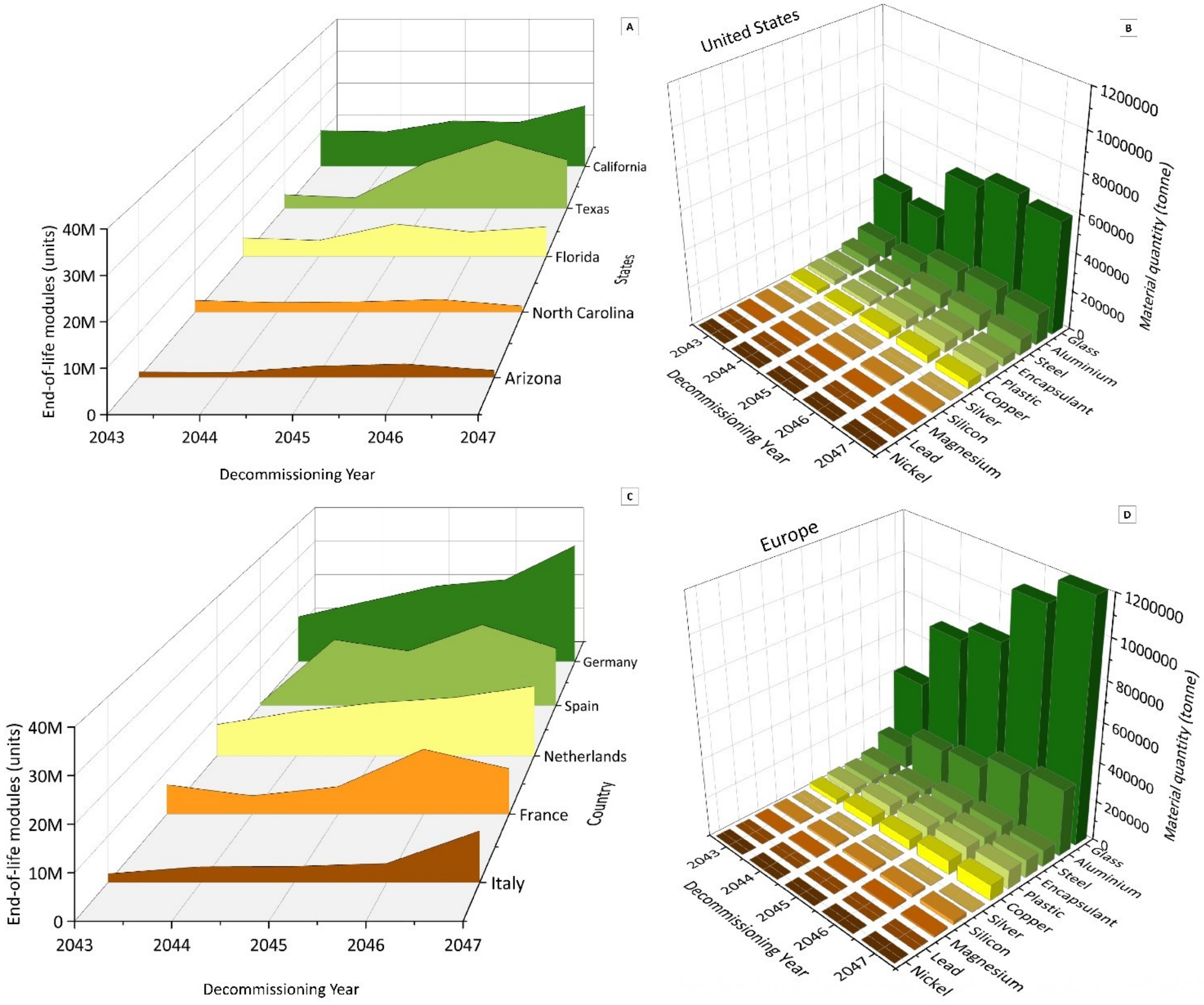

Fig. 4: Predicted EoL PV crystalline modules (M: million) based on installation years for five US states (A) and five European countries (C) with their respective PV waste's material composition (B and D).

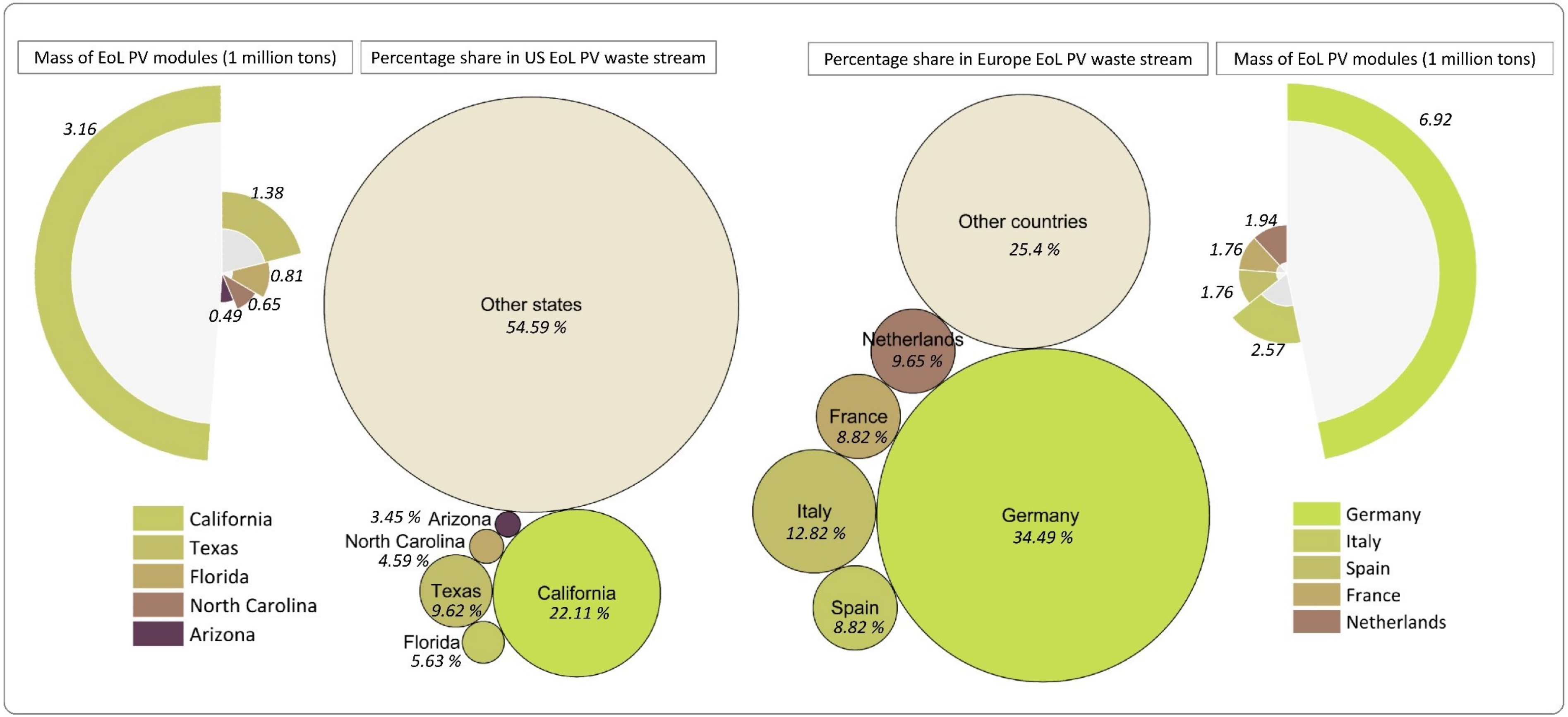

Fig. 5: Percentage-wise, the US state and European countries share in the EoL PV waste stream based on 2000-2022 installations.

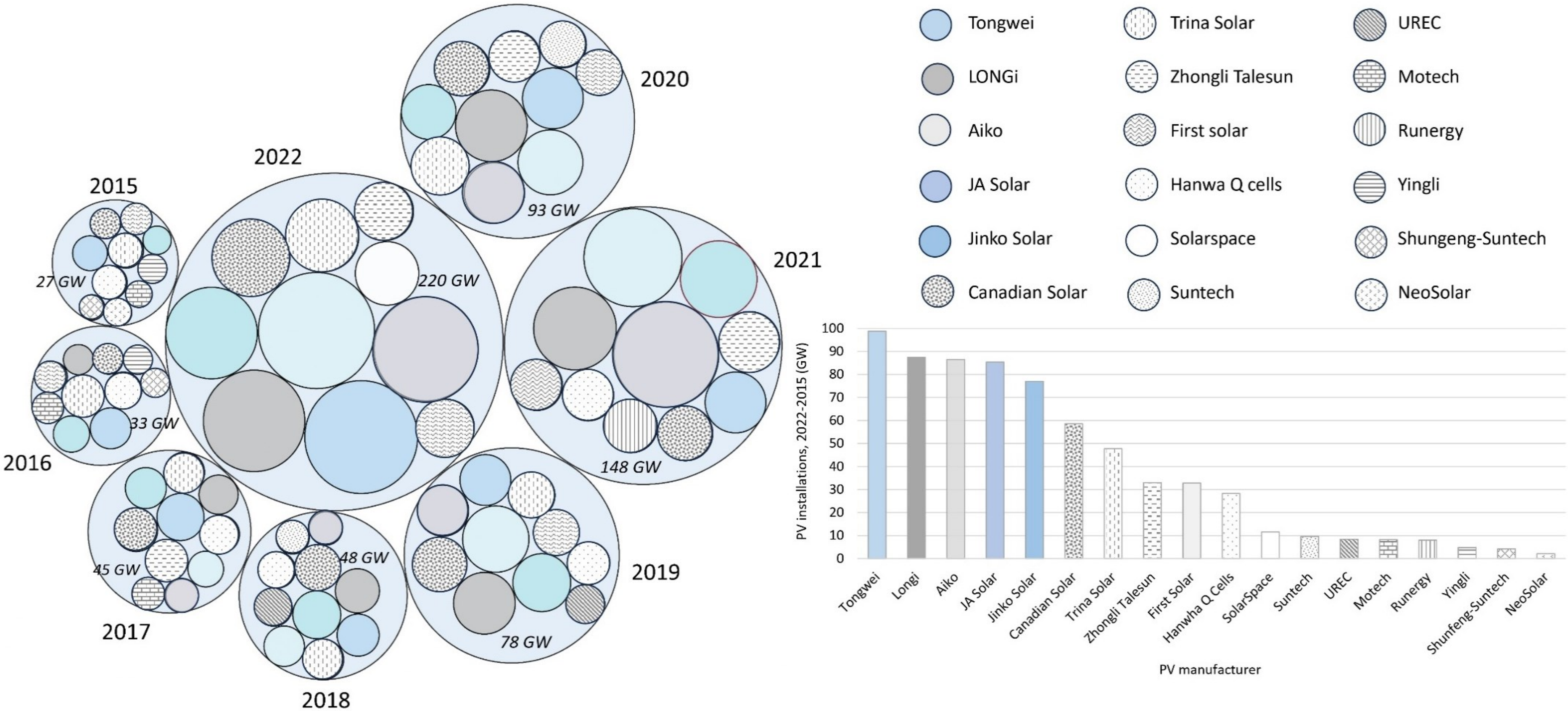

Fig. 6: Global Leading PV Manufacturers by Shipments (GW) (2015-2022) (Note: bubble size denotes the PV capacity shipments by manufacture; capacity number in the bubble denotes total PV capacity shipments from that respective year; solid-filled bubbles are shipments by the top five manufacturers)

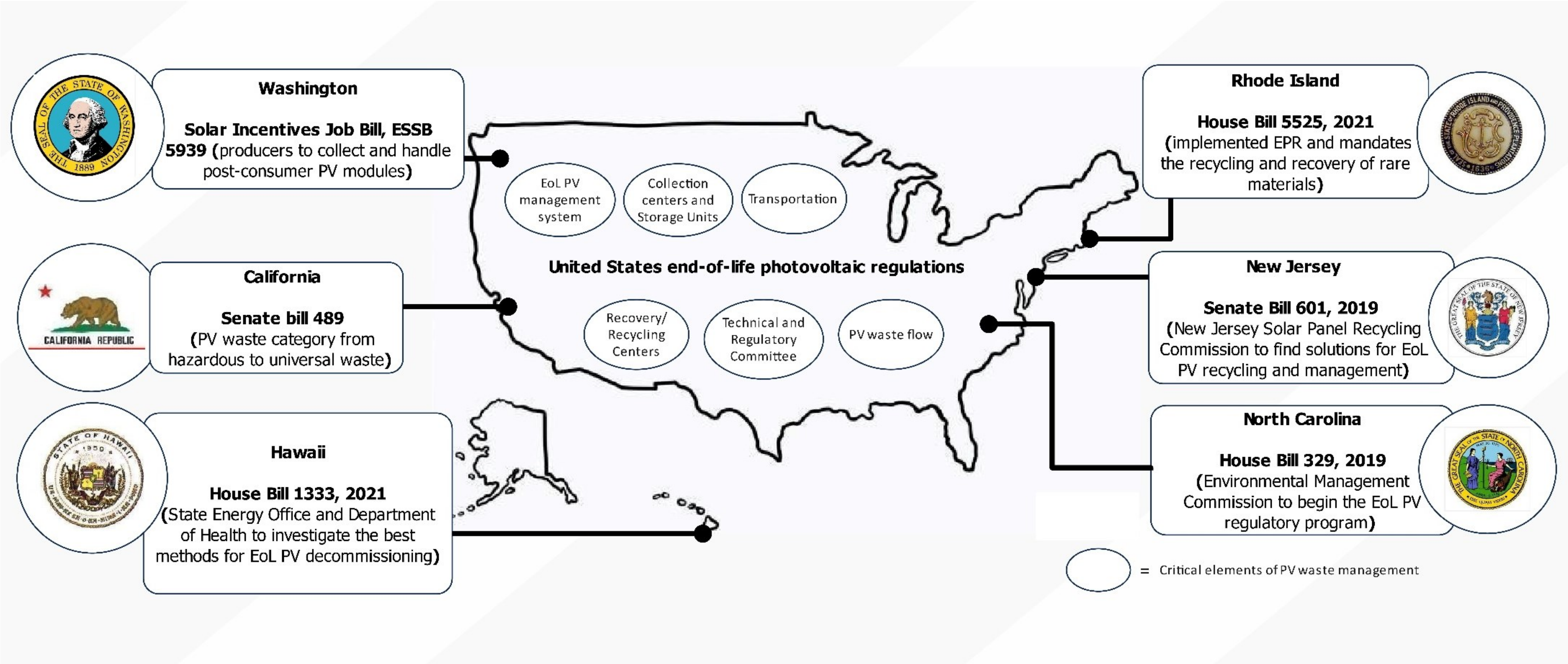

Fig. 7: United States-specific regulations towards EoL photovoltaics.

3.3 End-of-life solar PV regulations

3.3.1 United States end-of-life solar PV regulations

The US is among the world's top five countries for solar power generation. California (37 GW) and Texas (15 GW) have the most installed modules, followed by Massachusetts, Utah, and New York. In the US, large-scale PV deployment began around the year 2000. In the next 20 years, approximately 2 MT of solar scrap is expected in the US [45]. However, this estimate can be higher if solar plants are repowered more frequently for economic benefits. The increasing waste volume in the US led to the national discussion on suitable EoL management solutions. A small fraction of it is recycled (less than 10%); the rest is stored until sufficient volume is there and a cost-effective recycling option develops [46]. Modules could end up in landfills if proper regulatory directives and recycling systems are not implemented when they reach end-of-life [47]. No dedicated recycling facility has been developed in the US owing to the small volume of c-Si waste.

As of November 2023, no federal regulations address end-of-life PV waste management, and general electronic waste laws apply [46, 48]. There are no recovery and recycling requirements specific to solar modules by federal and state governments (except Washington) [49]. The high recycling cost and lack of recycling facilities make it difficult to enforce recycling regulations. However, the US Environmental Protection Agency plans to propose new PV recycling requirements in response to a petition submitted by a broad coalition of industry associations [50]. This amendment in the Resource Conservation and Recovery Act would clarify the management of EoL solar modules. The proposed regulations will encourage the development of municipal and commercial collection and recycling programs, reducing the disposal of PV waste in landfills [50].

In the meantime, some states like California and Washington are implementing regulations for PV waste handling without national policies. The recently enacted laws by the US states (Fig. 7) could improve domestic material recovery and US recycling. Washington has required solar manufacturers since July 2023 to fund the take-back and recycling of modules installed in the state after July 2017 (Table 3). In recent years, some states like Hawaii and Rhode Island proposed bills in 2021 and created advisory groups to investigate best practices for EoL PV waste handling. In addition, approximately 15 state bills were proposed to address EoL PV waste since 2014 but failed [48]. If the proposed bills are enacted, they will address the reuse and recycling of PV waste.

The lack of recycling facilities and regulations encouraged voluntary efforts to fill the gap (Table 4). Some companies, such as “Solar World” and “We Recycle Solar”, have leadership in establishing their recycling and material recovery framework [42, 45]. A voluntary program of solar manufacturers, SEIA (Solar Energy Industries Association), consists of more than 1000 US companies to promote PV recycling in the USA [7]. The SEIA receives and processes approximately 100 tons of crystalline PV waste monthly, separates bulk materials like glass, and sends unwanted materials to other recyclers [38]. Some SEIA members offer to refurbish and resell PV equipment or engage with suitable waste handlers.

For sustainable management and circular economy of solar PV’s critical materials, regulations are required to repurpose or recycle solar PVs. For example, California DTSC issued regulations for collecting, transporting, storing, and treating EoL PV waste via a permit-issuing process for PV manufacturers at no cost to owners [51]. Without state or federal regulations, industry standards can guide end-of-life PV management. For instance, reliability standards for certifying early retired modules for second-life applications can improve consumer confidence.

3.3.2 European Union end-of-life solar PV regulations

With the aim of sustainable production and consumption, the EU revised its WEEE directive in 2012 (2012/19/EU) and became the first one in the world to include PV waste in its electronic waste management chain. This revised directive included Extended Producer Responsibility (EPR), which requires producers to collect and recycle their installed modules at the EoL stage [52]. As per the directive, 85% of materials must be recovered in decommissioned modules. The directive applies to international manufacturers installing modules in Europe. After implementing the directive, a significant increase in research on recycling methods was observed [53].

Germany adopted the revised WEEE directive in 2015 and collected nearly 8,000 tons of PV waste in 2018. It implemented a collective producer compliance system and covered the management and recycling costs following two levels. Level 1 covers the cost of installed modules from producers based on their market share, and level 2 covers the future waste PV's management cost [49]. Italy adopted the revised directive in 2014 into its national policy guidelines. Switzerland included PV waste in its SENS foundation. It established SWICO RECYCLING (Swiss Industrial Association Swico) in 2015, providing financial support for PV recycling, and has collected 70 tons of PV waste since then. Other countries like Norway and the Czech Republic included the EU WEEE directive in their national legislation. They mandated solar PV producers and operators to manage waste from their PV installations [25].

In the last ten years, the EU introduced several standards specifying technical details for handling PV waste and treatment. Standard EN 50625-1 [54] regulates the WEEE treatment and emphasizes special care to avoid injury while handling PV's broken glass. DIN EN 50625-2-4 regulates the specific treatment requirements for EoL modules [55]. It specifies the handling of silicon PV from non-silicon-based modules and, further, the dismantling of modules into different materials. DIN CLC/TS 50625-3-5 [56] gives the technical specification for the PV module's de-pollution. The responsibilities between producers, state governments, and the EU are not clearly defined in all these directives.

The EU also established a non-profit organization, “PV Cycle”, to assist the PV manufacturers in Europe with waste management and regulations compliance [57]. PV Cycle is a volunteer effort taken by leading PV producers to manage decommissioned PV waste. Since 2007, the company has worked to align collection points, transportation, and recycling partners. To summarize, every EU country has a national WEEE register, which obligates to report the amount of installed PV modules and guarantee the collection and recycling plans and targets. Germany and France have dedicated PV recycling facilities, with process development being funded by the European Commission. Germany and France reported to collect 553 tons and 84 tons of PV modules in 2017, respectively [32].

Current EoL PV regulations have no regulations for emerging contaminants like PFAS (per- and poly-fluoroalkyl substances) and microplastics. Despite their co-occurrence in electronic waste, PFAS and microplastic contaminants are not mentioned in any regulations by US states and the EU. Both pollutants are not single contaminants but a group of substances that can pose serious health issues and environmental toxicity [58]. In addition to being toxic in its initial form, polymeric PFASs could undergo unclear degradation mechanisms to produce microplastics, such as polyvinyl fluoride (PVF) and polytetrafluorethylene (PTFE). Also, PFAS can adsorb on the surface of microplastics and may desorb in aquatic species when released into the environment; thus, microplastics can increase PFAS toxicity [59]. The author wants to highlight these contaminants, which should be incorporated into upcoming PV waste regulations. The regulation processes and EoL management framework need to include emerging concerns regarding PFAS and microplastics from PV waste [49].

Table 3: The US state-specific initiatives toward PV waste

State	Regulations/Policy	Year	Reference
California	*CalRecycle* (California's Department of Resources Recycling and Recovery) guides tracking, collecting, transporting, and recycling EoL solar waste.	2021	[51] [60]
	DTSC (California Department of Toxic Substances Control) issued regulations for collecting, transporting, storing, and treating EoL PV waste via a permit-issuing process for PV manufacturers.	2019	
	Senate Bill 489 states that the DTSC can change the PV waste category from hazardous to universal waste. In 2020, the EPA authorized it but did not mandate recycling.	2015	
	Title 22 requires PV manufacturers to take responsibility for recycling modules installed in California and report the progress.	2015	
New York	*Solar Guidebook* by New York State provides guidelines on decommissioning large-scale solar panel systems at their end of life, ensuring the land returns to its original condition, and recycling the solar components.	2023	[61]
Washington	*HB 2645* mandating PV module manufacturers to submit stewardship plans. It includes setting up a PV management group (Work Group) to review and provide recommendations for EoL PV management.	2020	[62] [63]
	Solar Incentives Job Bill, ESSB 5939, implemented the EPR principle, requiring producers to collect and handle post-consumer PV modules. It aims to reduce waste by recycling and create new job opportunities. Starting in 2017, producers with installed modules must bear some recycling costs. It initially covered residential solar waste but included utility/commercial PV waste in 2019.	2017	
North Carolina	*House Bill 329* required the Environmental Management Commission to begin the EoL PV regulatory program. Department of Environmental Quality classifies solar PV waste as universal waste. This only covers utility-scale installations.	2019	[64]
New Jersey	*Senate Bill 601* to establish the New Jersey Solar Panel Recycling Commission to find solutions for EoL PV recycling and management	2019	[65]
Hawaii	*House Bill 1333* requires the State Energy Office and the Department of Health to investigate the best methods for EoL PV decommissioning.	2021	[66]
Arizona	*House Bill 2828* intends to ban the disposal of solar waste in municipal solid landfills.	2020	[67]
Rhode Island	*House Bill 5525* implemented EPR and mandated the recycling and recovery of rare materials.	2021	[68]

Table 4: Industry and State-led Initiatives in the US

Initiative	Agency	Details
National PV Recycling Program	Solar Energy Industries Association	This voluntary program focuses on collaborating with industries with prior expertise in recycling glass, polymerics, aluminum, scrap metal, and electronics.
Solar Panel Recycling Initiative	Illinois Sustainable Technology Center, University of Illinois	In 2017, ISTC formed an EoL PV management working group with experts across various sectors to develop technical and economic solutions for sustainable management of PV waste.
Minnesota Solar Energy Industries Association	Minnesota Pollution Control Agency, Minnesota Department of Commerce,	In 2019, a working group was formed to investigate solutions for the safe and sustainable management of PV waste
Recycle PV Solar	Recycle PV	Recycle PV, founded in 2011, recycles PVs at its recycling facility in Arizona and provides used modules for second-life use.
Solarcycle	Solarcycle	Solarcycle, located in Texas, repair, refurbish, reuse, and recycle solar systems.
Good Sun	Good Sun	Good Sun, founded in 2013 in California, sells used silicon modules and BOS at discounted rates for secondary applications.

3.4 Fate of solar PV waste

This section attempts to assess the fate of EoL PV waste estimated in section 3.1 based on regulations summarized in section 3.2. There are no federal regulations for the US, and only two states, Rhode Island and Washington, have active regulations for EoL PV waste. Other states like California, New Jersey, and Arizona have proposed regulations that have not yet been implemented. Rhode Island and Washington have a cumulative installed PV capacity of 0.72 GW and 0.63 GW in 2022, respectively [7], and are projected to have 2 GW installations by 2025. So, the fate of the remaining cumulative PV installations in the US is uncertain. Further, it is assumed that recycling organizations like GoodSun and Solarcycle are handling early retired or suddenly environmentally damaged solar modules, which were not considered while estimating the EoL PV waste.

However, most European countries have EoL PV regulations and frameworks in place. Countries have adopted the WEEE directive in their national legislations and have country-specific PV manufacturer compliance schemes too. Thus, all the generated PV waste is assumed to be collected, handled, and recycled (Fig. 8).

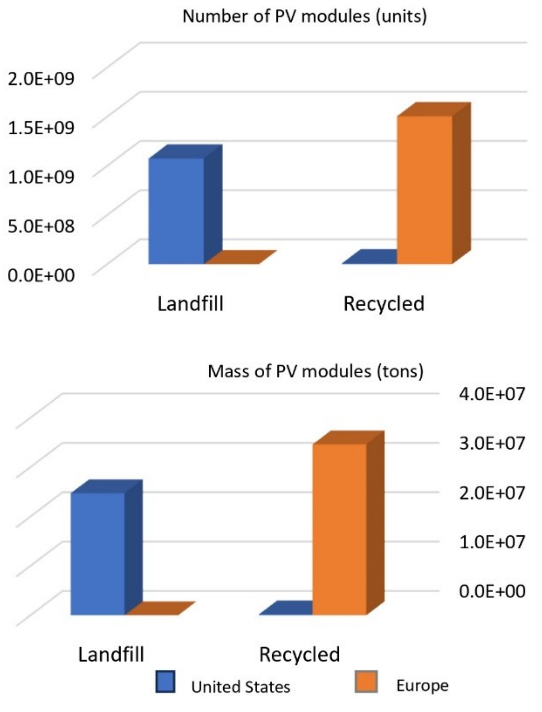

Fig. 8: Estimated fate of EoL solar modules generated between 2025-2050 as per present regulations in the United States and European Union.

The lifetime of crystalline solar modules is generally 25 to 30 years, which gives an impression of a low volume of waste at present, resulting in delay or non-inclusion of EoL PV waste in legislation. Recycling solar PVs is the preferred option, preventing the materials from being released into the environment, recovering rare materials, and reducing the waste volume. Recently, researchers have been developing cost-effective alternatives to managing solar PV waste as the volume is increasing sharply.

The estimated fate of PV waste in this section seems to be unrealistic due to the high uncertainty of future legislation. For example, many proposed bills in the US could rapidly change the volume of waste being recycled rather than landfilled. We report the worst-case scenario based on the current legislation which would lead to mostly landfilling of solar modules. To prevent this worst-case scenario from happening, the author highlights the urgent need for federal and state EoL PV regulations for the safe management of PV waste.

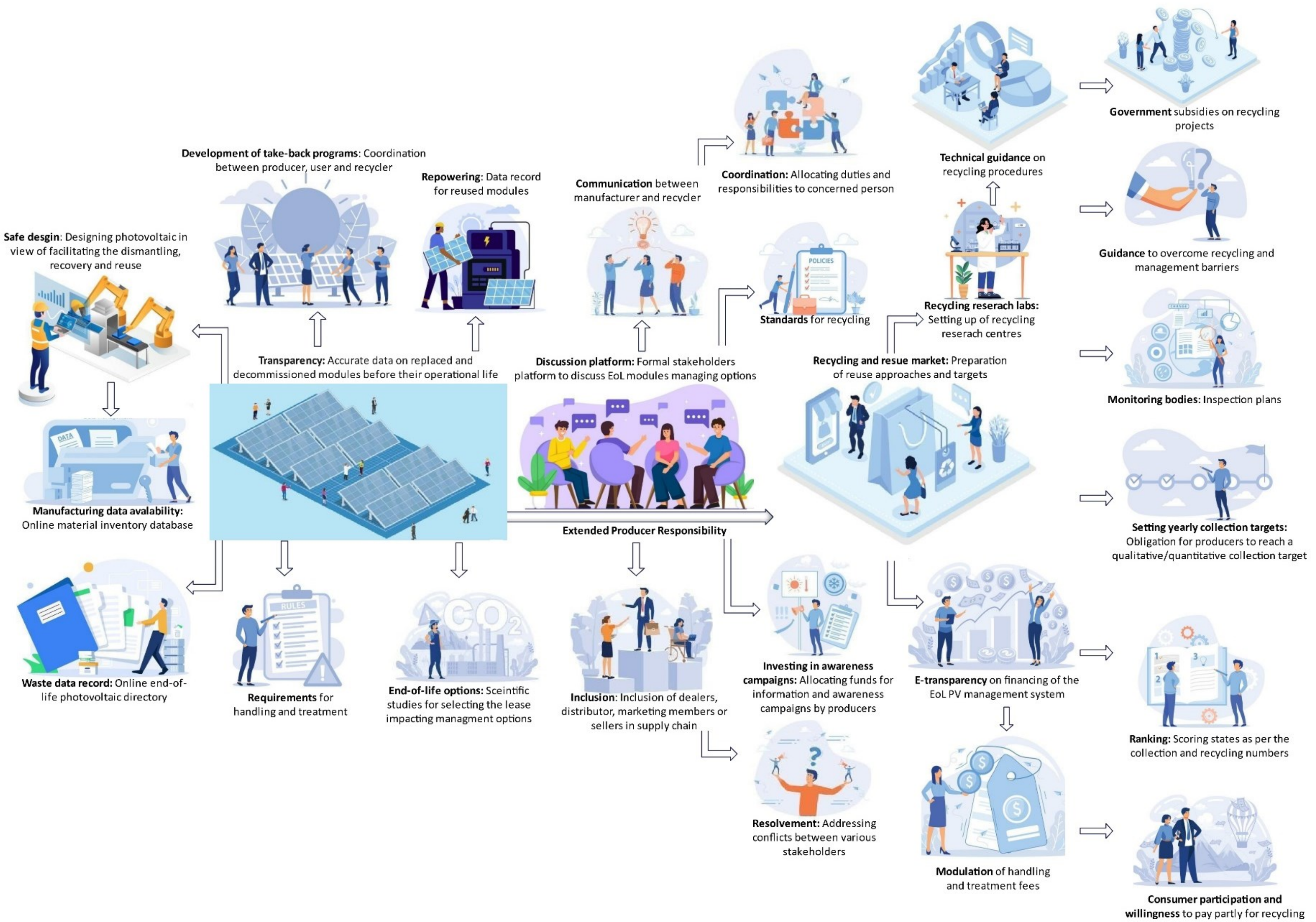

Fig. 9: Recommendations for end-of-life solar photovoltaics management

3.5 Recommendations for improvement in end-of-life solar photovoltaics management

Based on practices followed by Europe and the United States, the study outlines the following recommendations (Fig. 9):

1. **Implementation of EPR principle**: The European Union has implemented EPR by establishing close coordination between public and private parties, either by a central authority or by providing a common platform for discussion [69]. No EPR format or style is considered best; the performance depends on location and experience. Considering the high PV installation rate, this could be applied in the United States, especially California, Texas, and Arizona. California, the solar leader in the US, has no PV waste disposal regulations and plans; however, a project (to be administered) regulates solar equipment waste [70].
2. **Reuse and recycling market**: Recycling infrastructure and facilities are considered significant barriers to EoL solar waste management [71]. Setting up reuse and recovery centers with authorized/certified operators at the national level could be highly beneficial. This requires investing in recycling research and infrastructure (i.e., collection points) with government subsidies and multi-stakeholder funding. Companies like "SecondSol" and "We Recycle Solar" are emerging US recyclers for PV waste. This approach could further be applied by major EU and US PV manufacturers to meet the Electronic Product Environmental Assessment Tool (EPEAT) criteria for low-carbon solar modules.
3. **Communication and coordination**: Adequate communication channels could speed up all processes. Dedicated discussion platforms for communications could reduce conflicts and result in the inclusiveness of all stakeholders at different levels. Unclear roles and responsibilities between other parties also create conflicts. Clear multi-level stakeholder communication and coordination improve the system's different work units. More organisations like ‘PV Cycle’ can be established to provide a system to interact and communicate, which can help various stakeholders understand the needs and requirements of each other.
4. **Transparency**: Transparency in data and information at various stages from production (i.e., obliged to publish material composition data) and installation (i.e., number of modules installed per location) to after the end-of-life stage (i.e., number of units collected and handled) is critical [72]. Reporting materials data at every stage is a prerequisite for improving waste management. The obligation to report by all stakeholders enhances transparency and facilitates the environmentally responsible decisions. PV manufacturers and other companies across the solar supply chain need to report all materials use and waste release data at every stage.
5. **Consumer participation**: Understanding consumers' willingness to participate and pay (WTP) towards dismantling and recycling PVs is required for establishing a feasible collection and recycling system. Modulating recycling fees for different stakeholders depending on the actual cost of waste management is another crucial aspect to consider [73]. Users can help in PV waste management by contributing a small portion towards the recycling cost.

6. **Monitoring process and collection targets**: Regular inspections of all operators working on take-back and collection programs to record the waste handling practices. Setting up collection targets for manufacturers and states could increase the EoL module collection rates. Further, ranking and challenging to meet specific yearly targets may encourage manufacturers to set EoL module handling as one of the priority jobs. The recyclers can monitor the PV waste generation at different locations to effectively plan the recycling and recovery operations.
7. **Roles and responsibilities**: A clear definition of responsibilities for involved stakeholders results in the efficient operation of PV waste management. Addressing the conflicting questions about roles needs to be done at all levels, respecting the different opinions of all stakeholders.
8. **Information availability**: Regulations/Guidebooks that mandate or encourage manufacturers to provide PV modules with descriptions of materials composition (along with hazardous substances such as lead) could enable information available for various stakeholders (such as researchers and regulators) and can eliminate the need for hazardous waste characterization. The access to documentation on material usage, installation, and PV failure could result in more transparency between manufacturers and EoL regulators.
9. **Economic Incentives**: Manufacturers have always highlighted the lack of recycling incentives in the past [71]. Reports suggest that recycling costs $15-45 per module in the US, while disposal fees are <$1 per module in non-hazardous landfills and <$5 per module at hazardous waste landfills [48]. Federal, state, or private organizations-funded grants are required to promote the safe handling and design of easy-to-recycle processes.
10. **State or Regional Waste Plans**: The transportation cost of EoL PVs to destined recycling and management facilities is costly. There is a limitation concerning permitting approvals, collection vehicles, and transport haulers [7]. Thus, setting up regional management facilities while state collection and recycling frameworks are established is another approach that could be adopted.

4. Conclusion and way forward

This study aims to compare the end-of-life PV waste management practices in the European Union and the United States as per the present regulations. To summarize, the main contributions of this work include (1) projections of the crystalline silicon PV waste volumes by 2050 for the US and the EU, (2) an overview of PV waste regulations in the EU and the US, (3) a comparison of PV waste management for five US states and five European countries with highest installation capacity, (4) consequent disposal of PV waste as per the present regulations, (5) recyclability and material recovery potential from PV waste, (6) recommendations for improvement in end-of-life solar photovoltaics management.

The analysis shows that the end-of-life PV waste in 2050 will have approximately 200B USD worth of materials recovery potential. However, the recycling facilities and the US's regulations and management frameworks for EoL modules are still under development. State- and industry-led policies and initiatives have emerged to address EoL PV module management. The EU introduced several standards in the last ten years, specifying technical details for handling PV waste and treatment. Voluntary organizations like PV Cycle and SEIA work to promote EoL PV management. Since promising commercialized recycling technologies are unavailable, government subsidies could allow private investments to start. Some US states like Arizona and Texas, which are early at the stage of addressing EoL PV management challenges, can use the other states or EU's expertise in developing regulatory frameworks and management guidelines.

Overall, this paper attempts to determine the amount of EoL PV modules along with the active and proposed regulations for managing it. The analysis is intended to provide a preliminary analysis of upcoming PV waste and regulations status. However, the following potential research actions are needed for a more comprehensive PV waste estimation which can serve as a basis for establishing the EoL PV panel management system:

- potential increase in PV waste due to damage from natural disasters or early loss scenarios
- increase in PV waste due to the early retirement of solar modules with lower efficiency to higher efficiency modules.
- quantify the waste due to balance-of-systems, packaging, cables.
- quantify the waste from broken modules generated during manufacturing and transportation.
- consider the temporal change in material composition in solar modules on PV waste materials.

Acknowledgment

This work was supported by the National Science Foundation grant number NSF 2044886.

References

[1] P. Baliozian *et al.*, “The international technology roadmap for photovoltaics and the significance of its decade-long projections,” in *37th European PV Solar Energy Conference and Exhibition*, 2020, p. 11.

[2] International Energy Agency, “IEA PVPS Task 1 Strategic PV Analysis and Outreach,” *Photovoltaic Power Systems Programme*, Apr. 2023.

[3] L. L. Barnes, “Environmental Impact of Solar Panel Manufacturing and End-of-Life Management: Technology and Policy Options,” 2017.

[4] I. Annex III, “Technology-specific cost and performance parameters,” *IPCC. Climate Change*, 2014.

[5] J. D. Santos and M. C. Alonso-García, “Projection of the photovoltaic waste in Spain until 2050,” *J Clean Prod*, vol. 196, pp. 1613–1628, 2018.

[6] J. A. Tsanakas *et al.*, “Towards a circular supply chain for PV modules: Review of today’s challenges in PV recycling, refurbishment and re-certification,” *Progress in Photovoltaics: Research and Applications*, vol. 28, no. 6, pp. 454–464, 2020.

[7] “SEIA (Solar Energy Industries Association),” 2019.

[8] IEA, “Solar PV reports,” Solar PV reports.

[9] I. Irena, “End-of-life management: Solar photovoltaic panels,” *International Renewable Energy Agency and International Energy Agency Photovoltaic Power Systems*, 2016.

[10] EPIA, “European Photovoltaic Industry Association .”

[11] D. Sah and S. Kumar, “Recovery and analysis of valuable materials from a discarded crystalline silicon solar module,” *Solar Energy Materials and Solar Cells*, vol. 246, p. 111908, 2022.

[12] J. R. Duflou, J. R. Peeters, D. Altamirano, E. Bracquene, and W. Dewulf, “Demanufacturing photovoltaic panels: Comparison of end-of-life treatment strategies for improved resource recovery,” *CIRP Annals*, vol. 67, no. 1, pp. 29–32, 2018.

[13] L. Yuan and A. Anctil, “Material Use and Life Cycle Impact of Crystalline Silicon PV Modules Over Time,” in *2022 IEEE 49th Photovoltaics Specialists Conference (PVSC)*, IEEE, 2022, pp. 1028–1030.

[14] M. Kavousi and E. K. Alamdari, “A Comprehensive and Sustainable Recycling Process for Different Types of Blended End-of-Life Solar Panels: Leaching and Recovery of Valuable Base and Precious Metals and/or Elements,” *Metals (Basel)*, vol. 13, no. 10, p. 1677, 2023.

[15] A. Divya, T. Adish, P. Kaustubh, and P. S. Zade, “Review on recycling of solar modules/panels,” *Solar Energy Materials and Solar Cells*, vol. 253, p. 112151, 2023.

[16] J. R. Peeters, D. Altamirano, W. Dewulf, and J. R. Duflou, “Forecasting the composition of emerging waste streams with sensitivity analysis: A case study for photovoltaic (PV) panels in Flanders,” *Resour Conserv Recycl*, vol. 120, pp. 14–26, 2017.

[17] S. Mahmoudi, N. Huda, and M. Behnia, “Critical assessment of renewable energy waste generation in OECD countries: Decommissioned PV panels,” *Resour Conserv Recycl*, vol. 164, p. 105145, 2021.

[18] P. Dias, S. Javimczik, M. Benevit, H. Veit, and A. M. Bernardes, “Recycling WEEE: Extraction and concentration of silver from waste crystalline silicon photovoltaic modules,” *Waste Management*, vol. 57, pp. 220–225, 2016.

[19] A. Domínguez and R. Geyer, “Photovoltaic waste assessment in Mexico,” *Resour Conserv Recycl*, vol. 127, pp. 29–41, 2017.

[20] Heather Mirletz, Henry Hieslmair, Silvana Ovaitt, TaylorL. Curtis, and Teresa M. Bares, “Unfounded concerns about photovoltaic module toxicity and waste are slowing decarbonization,” *Nat Phys*, Oct. 2023.

[21] D. Ravikumar *et al.*, “Environmentally improved CdTe photovoltaic recycling through novel technologies and facility location strategies,” *Progress in Photovoltaics: Research and Applications*, vol. 28, no. 9, pp. 887–898, 2020.

[22] C. C. Farrell *et al.*, “Technical challenges and opportunities in realising a circular economy for waste photovoltaic modules,” *Renewable and Sustainable Energy Reviews*, vol. 128, p. 109911, 2020.

[23] L. L. Barnes, “Environmental Impact of Solar Panel Manufacturing and End-of-Life Management: Technology and Policy Options,” 2017.

[24] M. K. Khawaja, M. Ghaith, and A. Alkhalidi, “Public-private partnership versus extended producer responsibility for end-of-life of photovoltaic modules management policy,” *Solar Energy*, vol. 222, pp. 193–201, 2021.

[25] A. Sharma, S. Pandey, and M. Kolhe, “Global review of policies & guidelines for recycling of solar PV modules,” *Int. J. Smart Grid Clean Energy*, vol. 8, no. 5, pp. 597–610, 2019.

[26] A. Domínguez and R. Geyer, “Photovoltaic waste assessment of major photovoltaic installations in the United States of America,” *Renew Energy*, vol. 133, pp. 1188–1200, 2019.

[27] J. Pastuszak and P. Węgierek, “Photovoltaic Cell Generations and Current Research Directions for Their Development,” *Materials*, vol. 15, no. 16, p. 5542, 2022.

[28] D. Feldman, K. Dummit, J. Zuboy, and R. Margolis, “Fall 2022 Solar Industry Update,” National Renewable Energy Lab.(NREL), Golden, CO (United States), 2022.

[29] A. Jäger-Waldau, “PV status report 2019,” *Publications Office of the European Union: Luxembourg*, pp. 7–94, 2019.

[30] Luyao Yuan, Preeti Nain, Mallika Kothari, and Annick Anctil, “Material Intensity and Carbon Footprint of Crystalline Silico n Module Assembly Over Time,” *Solar Energy*, vol. 269, no. 112336, Feb. 2024.

[31] Bloomberg, “Market commodities, Precious and Industrial Metals.”

[32] G. A. Heath *et al.*, “Research and development priorities for silicon photovoltaic module recycling to support a circular economy,” *Nat Energy*, vol. 5, no. 7, pp. 502–510, 2020.

[33] J. Trube, “International Technology Roadmap for Photovoltaic.” ITRPV)(VDMA, 2018), 2020.

[34] D. Gielen, “Critical minerals for the energy transition,” *International Renewable Energy Agency, Abu Dhabi*, 2021.
[35] David Feldman, Krysta Dummit, Jarett Zuboy, and Robert Margolis, “Summer 2023 Solar Industry Update.”
[36] C. Deng, J. T. Stid, P. Nain, and A. Anctil, “Identification of Module Replacements in US Utility-Scale Photovoltaic Installations,” in *2023 IEEE 50th Photovoltaic Specialists Conference (PVSC)*, IEEE, 2023, pp. 1–3.
[37] A. Limmanee *et al.*, “A Survey of Decommissioned Photovoltaic Modules from Solar Power Plants in Thailand: Performance and Second Life Opportunities,” *IEEJ Transactions on Electrical and Electronic Engineering*, vol. 18, no. 12, pp. 1967–1972, 2023.
[38] Solar Energy Industry Association, “SEIA 2023 research data.”
[39] R. M. Elavarasan *et al.*, “A comprehensive review on renewable energy development, challenges, and policies of leading Indian states with an international perspective,” *Ieee Access*, vol. 8, pp. 74432–74457, 2020.
[40] Z. Fareed and U. K. Pata, “Renewable, non-renewable energy consumption and income in top ten renewable energy-consuming countries: Advanced Fourier based panel data approaches,” *Renew Energy*, vol. 194, pp. 805–821, 2022.
[41] E. Kastanaki and A. Giannis, “Energy decarbonisation in the European Union: Assessment of photovoltaic waste recycling potential,” *Renew Energy*, vol. 192, pp. 1–13, 2022.
[42] S. P. Europe, “Global market outlook for solar power 2015–2019,” *Euoropean Photovoltaic Industry Association, Bruxelles, Tech. Rep*, 2015.
[43] D. Feldman, K. Dummit, J. Zuboy, and R. Margolis, “Spring 2023 Solar Industry Update,” National Renewable Energy Lab.(NREL), Golden, CO (United States), 2023.
[44] Issac Orr, “Solar ‘farm’ components are starting to fail after only 10 to 15 years,” *American Experiment*, Oct. 2023. Accessed: Oct. 25, 2023. [Online]. Available: https://www.americanexperiment.org/solar-farm-components-are-starting-to-fail-after-only-10-to-15-years/
[45] C. Vargas and M. Chesney, “End of life decommissioning and recycling of solar panels in the United States. A real options analysis,” *Journal of Sustainable Finance & Investment*, vol. 11, no. 1, pp. 82–102, 2021.
[46] NREL (National Renewable Energy Laboratory), “Photovoltaics in the Circular Economy Workshop,” *Golden, Colorado*, 2019.
[47] A. Domínguez and R. Geyer, “Photovoltaic waste assessment of major photovoltaic installations in the United States of America,” *Renew Energy*, vol. 133, pp. 1188–1200, 2019.
[48] T. L. Curtis, H. Buchanan, G. Heath, L. Smith, and S. Shaw, “Solar photovoltaic module recycling: a survey of US policies and initiatives,” National Renewable Energy Lab.(NREL), Golden, CO (United States), 2021.
[49] A. Yadav, “Investigate technical, policy and business approaches to addressing stewardship and circularity for end-of-life for PV system,” 2021.
[50] US Environmental Protection Agency, *Improving Recycling and Management of Renewable Energy Wastes: Universal Waste Regulations for Solar Panels and Lithium Batteries*. United States, 2023. Accessed: Oct. 26, 2023. [Online]. Available: https://www.epa.gov/hw/improving-recycling-and-management-renewable-energy-wastes-universal-waste-regulations-solar
[51] Department of Toxic Control Substances California, “DTSC Regulations (2019).”
[52] A. Han, E. Han, and E. Han Hv, “Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment,” *Harting: Espelkamp, Germany*, 2011.
[53] A. Sharma, S. Pandey, and M. Kolhe, “Global review of policies & guidelines for recycling of solar PV modules,” *Int. J. Smart Grid Clean Energy*, vol. 8, no. 5, pp. 597–610, 2019.
[54] European Union, *DIN EN 50625-1 (VDE 0042-13-1) Collection, logistics & treatment requirements for WEEE – Part 1: General treatment requirements*. 2014.
[55] European Union DIN EN 50625-2-4, *Collection, logistics & treatment requirements for WEEE – Part 2-4: Treatment requirements for photovoltaic panels*. 2017.
[56] European Union, *DIN CLC/TS 50625-3-5 VDE V 0042-13-35 Collection, logistics & Treatment requirements for WEEE*. 2017.
[57] J. A. Tsanakas *et al.*, “Towards a circular supply chain for PV modules: Review of today’s challenges in PV recycling, refurbishment and re-certification,” *Progress in Photovoltaics: Research and Applications*, vol. 28, no. 6, pp. 454–464, 2020.
[58] J. W. Scott, K. G. Gunderson, L. A. Green, R. R. Rediske, and A. D. Steinman, “Perfluoroalkylated substances (Pfas) associated with microplastics in a lake environment,” *Toxics*, vol. 9, no. 5, p. 106, 2021.
[59] K. Senathirajah and T. Palanisami, “Strategies to reduce risk and mitigate impacts of disaster: increasing water quality resilience from microplastics in the water supply system,” *ACS ES&T Water*, 2023.
[60] CalRecycle, “California’s Department of Resources Recycling and Recovery.” [Online]. Available: https://calrecycle.ca.gov/lgcentral/library/guidance/
[61] NYSERDA, “New York State Solar Guidebook.”
[62] P. Majewski *et al.*, “Recycling of solar PV panels-product stewardship and regulatory approaches,” *Energy Policy*, vol. 149, p. 112062, 2021.
[63] H. 2645, “Washington State Legislature,” 2019.
[64] H. 329, “North Carolina General Assembly,” 2019.
[65] S. 601, “New Jersey State Legislature,” 2019.
[66] Relating To Energy, “Hawaii State Legislature,H. 1333,” 2021.
[67] H. 2828 Solar; electric vehicle batteries; disposal, “ Arizona State Legislature,” 2020.
[68] Photovoltaic Takeback Act Of 2021, “H. 5525, State of Rhode Island General Assembly,” 2021.

[69] D. Hogg, C. Sherrington, J. Papineschi, M. Hilton, A. Massie, and P. Jones, "Study to Support Preparation of the Commission's Guidance for Extended Producer Responsibility Schemes," *Eunomia. Report for DG Environment of the European Commission*, 2020.

[70] N. Rathore and N. L. Panwar, "Strategic overview of management of future solar photovoltaic panel waste generation in the Indian context," *Waste Management & Research*, vol. 40, no. 5, pp. 504–518, 2022.

[71] H. K. Salim, R. A. Stewart, O. Sahin, and M. Dudley, "Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: A systematic literature review," *J Clean Prod*, vol. 211, pp. 537–554, 2019.

[72] M. Kling, F. Zotz, and D. Huranova, "WEEE compliance promotion exercise Final Report for EC," *Bipro and Deloitte (07.0201/2016/737282/ETI/ENV B. 3)*, 2017.

[73] P. Nain and A. Kumar, "Understanding manufacturers' and consumers' perspectives towards end-of-life solar photovoltaic waste management and recycling," *Environ Dev Sustain*, pp. 1–21, 2022.